# Can one see Coulomb-nuclear interference effects in nucleon-nucleus scattering?

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In Dirac phenomenology, a large Coulomb-nuclear interference term appears in the effective potential of the Schrödinger-like equation equivalent to the Dirac equation. This is apparently in strong contrast with the nonrelativistic approach and could be checked by a comparative study of neutron- and proton-nucleus scattering. A detailed calculation in a realistic case shows, however, that the interference effect is elusive.

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The relativistic approach has met considerable success in many nuclear physics problems both in nuclear structure and nuclear reaction studies. For bound state problems, it is possible to start from an effective meson-nucleon Lagrangian and reach a satisfactory description of atomic nuclei by using mean field or Dirac-Hartree-Fock approximation [1,2]. In the domain of nucleon-nucleus reactions at intermediate energies, the so-called Dirac phenomenology where optical model potentials are associated with the Dirac equation is a powerful tool for analyzing scattering data [3]. The common feature of the self-consistent relativistic mean field and the phenomenological Dirac optical potential is the appearance, in the nuclear component, of a strongly attractive scalar potential $S$ and a strongly repulsive vector potential $V$. In the case of protons, a Coulomb potential $V_c$ must be added to $V$.

The question of Coulomb-nuclear interference (CNI) arises when, starting from the Dirac equation for a proton, one derives a Schrödinger-like equation for the upper component of the Dirac spinor. Then, as we shall see explicitly below, the effective potential in the latter equation contains a term $-V_cV/M$ where $M$ is the nucleon rest mass. Since the potential Re$V$ is about 300–400 MeV at the nuclear center this CNI potential brings in an appreciable attraction which may lead to sizable effects on properties like the Coulomb energy of a proton bound in a potential well. This point was examined in Ref. [4] where it was found that the negative CNI potential is partly compensated by a strong energy dependence of the total effective potential but still a lowering of the proton Coulomb energy remains. However, a detailed comparison of Coulomb displacement energies in mirror nuclei calculated with relativistic and nonrelativistic self-consistent models shows that the differences between nonrelativistic and relativistic results do not exceed 300–400 keV [5]. To look for a more favorable case where the CNI effect would show up more clearly, it was suggested by Nogami *et al.* [6] to consider proton-nucleus and neutron-nucleus scattering at the same incident energy. Thus, one would get rid of the energy dependence effect which is inherent to the Coulomb displacement energy problem. In a schematic case, it was found [6] a large CNI effect on the low partial wave phase shifts. This result was intriguing enough to motivate the present study where this question is re-examined in a realistic situation, namely elastic nucleon-nucleus scattering at intermediate energies with realistic optical potentials.

Let us begin with the Dirac equation for a proton of total energy $W=M+E$ scattered by a complex optical potential whose scalar and vector components are $S(\vec{r})$ and $V(\vec{r})$:

$$[-i\vec{\alpha}\cdot\vec{\nabla}+\beta(M+S(\vec{r}))+V(\vec{r})+V_c(\vec{r})]\Psi(\vec{r})=W\Psi(\vec{r}), \tag{1}$$

where $\vec{\alpha}$ and $\beta$ are the Dirac matrices and we have used $\hbar=c=1$. A Schrödinger-like equation for the upper component $\Phi$ of the Dirac spinor $\Psi$ can be obtained by eliminating its lower component. It is customary to introduce the related function:

$$\tilde{\Phi}(\vec{r})\equiv[W+M+S(\vec{r})-(V(\vec{r})+V_c(\vec{r}))]^{-1/2}\Phi(\vec{r}), \tag{2}$$

which has the same asymptotic behavior as $\Phi(\vec{r})$. Then, the Schrödinger-like equation is

$$\left[-\frac{\nabla^2}{2M}+V_{\text{cent}}(\vec{r})+V_{\text{s.o.}}(\vec{r})\vec{L}\cdot\vec{s}\right]\tilde{\Phi}(\vec{r})=E\left(1+\frac{E}{2M}\right)\tilde{\Phi}(\vec{r}), \tag{3}$$

where the (complex) central and spin-orbit effective potentials are given by [7]

$$V_{\text{cent}}=S\left(1+\frac{S}{2M}\right)+(V+V_c)\left(1+\frac{2E-V-V_c}{2M}\right)+\frac{1}{2M}\left[\frac{1}{4}\left(\frac{B'}{1-B}\right)^2+\frac{1}{r}\left(\frac{B'}{1-B}\right)+\frac{1}{2}\left(\frac{B'}{1-B}\right)'\right], \tag{4}$$

$$V_{\text{s.o.}}=\frac{1}{Mr}\left(\frac{B'}{1-B}\right), \tag{5}$$

where

 

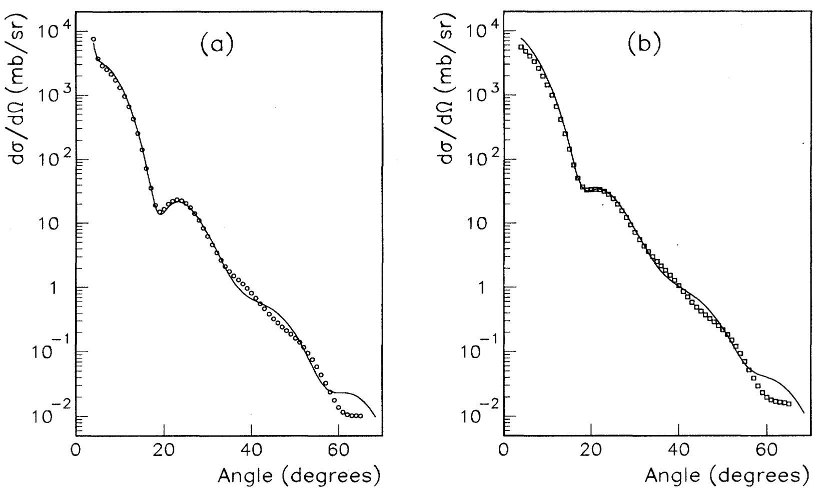


FIG. 1. Differential cross sections for $p$- and $n$-$^{40}$Ca scattering at $E=160$ MeV. Dots are pseudo-data points generated by Dirac phenomenology, curves are nonrelativistic calculations (see text). (a) protons; (b) neutrons.

$$B \equiv \frac{V+V_c-S}{2M+E}\,. \tag{6}$$

The main contribution to the central potential (4) is $S+V+V_c$, which is then modified by the term $-V_cV/M$ mentioned above and by other correction terms which are energy dependent or of smaller size.

Now, if we consider a $N=Z$ target nucleus, the scattering of a neutron at the same incident energy $E$ by this target would be described by the same equations (1)–(6) with $V_c$ set to zero and the same optical potential $(S,V)$ since there is no nuclear symmetry potential. Then, the difference between the proton and neutron effective central potentials has the form

$$V_{\rm cent}^{(p)}-V_{\rm cent}^{(n)}=V_c-\frac{V_cV}{M}+\Delta V_{\rm cent}\,. \tag{7}$$

In the nonrelativistic approach the difference between proton and neutron optical potentials at the same energy $E$ contains, besides the term $V_c$, a (complex) contribution $\Delta U_c$ called the Coulomb correction term [8]:

$$V_{\rm opt}^{(p)}-V_{\rm opt}^{(n)}=V_c+\Delta U_c\,. \tag{8}$$

The term $\Delta U_c$ arises from the energy dependence of optical potentials and the fact that the Coulomb potential changes locally the kinetic energy of the incident proton. This Coulomb correction term would not exist if the nucleon optical potential were energy independent while the CNI term that we discuss here would still be present. Thus, one must distinguish between the CNI potential $-VV_c/M$ of the relativistic approach and the Coulomb correction term $\Delta U_c$ of nonrelativistic optical potentials even though their volume integrals are found to be of comparable magnitude in some situations [9].

The question is whether effects due to the CNI term $-V_cV/M$ can be compensated by other effects linked to the $\Delta V_{\rm cent}$ term. If this CNI effect really exists, it would be detected by performing proton and neutron elastic scattering at the same energy $E$ on a $N=Z$ nucleus and analyzing the measured angular distributions and spin observables by using relativistic and nonrelativistic optical potentials. This should be preferrably done in the intermediate energy range where both relativistic and nonrelativistic approaches are valid. Although such data exist for protons, the experimental situation for neutrons is far less known and does not allow such a comparison (see, e.g., Refs. [10–13]). For this reason, we have resorted to a procedure in which realistic pseudo-data are produced by the Dirac phenomenology and then analyzed

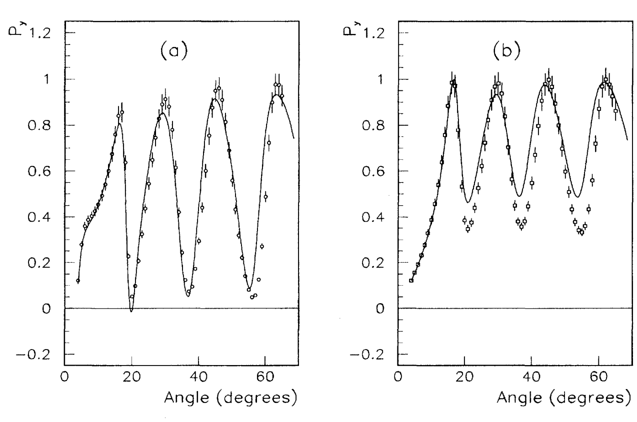


FIG. 2. Same as Fig. 1, for polarizations $P_y$.

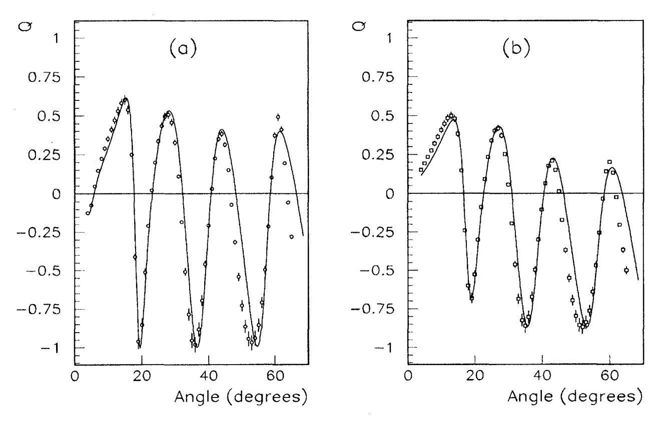


FIG. 3. Same as Fig. 1, for spin-rotation parameters $Q$.

by the nonrelativistic optical model.

We choose the target $^{40}$Ca and the incident energy $E=160$ MeV as a test case. Hama *et al.* [3] have given comprehensive parametrizations of Dirac optical potentials fitted on proton elastic scattering at energies 65 MeV$\leqslant E \leqslant$1040 MeV off target nuclei in the range $40 \leqslant A \leqslant 208$. These parametrizations reproduce well the measured differential cross-sections $d\sigma/d\Omega$, polarizations $P_y$, and spin-rotation parameters $Q$. Using parameter set 1 of Ref. [3] for the Dirac optical potentials $S$ and $V$ we have calculated by solving Eq. (3) the proton differential cross sections and spin observables:

$$P_y \equiv 2\frac{\mathrm{Re}(gh^*)}{|g|^2+|h|^2}, \tag{9}$$

$$Q \equiv 2\frac{\mathrm{Im}(gh^*)}{|g|^2+|h|^2}, \tag{10}$$

where the scattering amplitude is written as

$$T = g + h\vec{\sigma}\cdot\hat{n}, \tag{11}$$

with $\hat{n}$ being the unit vector perpendicular to the reaction plane. The calculated proton results are shown in Figs. 1(a)–3(a) as pseudo-data points. With the same potentials $S$ and $V$ we also calculate the corresponding neutron observables and report them as pseudo-data points in Figs. 1(b)–3(b). Next, a nonrelativistic optical potential $V_{\mathrm{opt}}^{(p)}$ is found by a least-square search on top of a standard optical model routine. The results of this $V_{\mathrm{opt}}^{(p)}$ are shown as curves in Figs. 1(a)–3(a). They reproduce perfectly well the proton pseudo-data. Then, in the spirit that the Coulomb correction term $\Delta U_c$ can be dropped the neutron optical potential is uniquely determined to be $V_{\mathrm{opt}}^{(n)} = V_{\mathrm{opt}}^{(p)} - V_c$. This is consistent with the underlying assumption that both relativistic optical potentials $(S, V)$ and nonrelativistic ones $(V_{\mathrm{opt}}^{(n)}, V_{\mathrm{opt}}^{(p)})$ are energy independent in the present model. This choice is made to single out effects of $-VV_c/M$, if any. With $V_{\mathrm{opt}}^{(n)}$ we calculate the neutron observables and report them as curves in Figs. 1(b)–3(b). The agreement with the neutron pseudo-data is practically at the same level as that for protons, except for some deviations in the fit of $P_y$ values at large angles which are slightly more pronounced for neutrons.

Thus, the relativistic and nonrelativistic approaches are perfectly equivalent for nucleon-nucleus scattering at intermediate energies and the CNI term has no visible effect. There are two main reasons for this. First, the potential $\Delta V_{\mathrm{cent}}$ defined by Eq. (7) contains several terms but the dominant one is $V_c E/M$. For $E \simeq 160$ MeV this term cancels about one-half of $\mathrm{Re}(-V_c V/M)$ in the nuclear interior, but more importantly this cancellation becomes more or less complete in the surface region where $\mathrm{Re}V/M$ approaches $E/M$. Second, the absorptive potential has the effect that the inner region becomes less important since scattering occurs largely around the surface region where the above cancellation works best and where the value of $V_c V/M$ is smaller anyway. The neglect of absorptive potential in Ref. [6] might be one of the reasons for finding large CNI effects in phase shifts.

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